

## Detector performance and requirements for top reconstruction at the LHC (ATLAS case)

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Questions for the “Top algorithms and detectors”

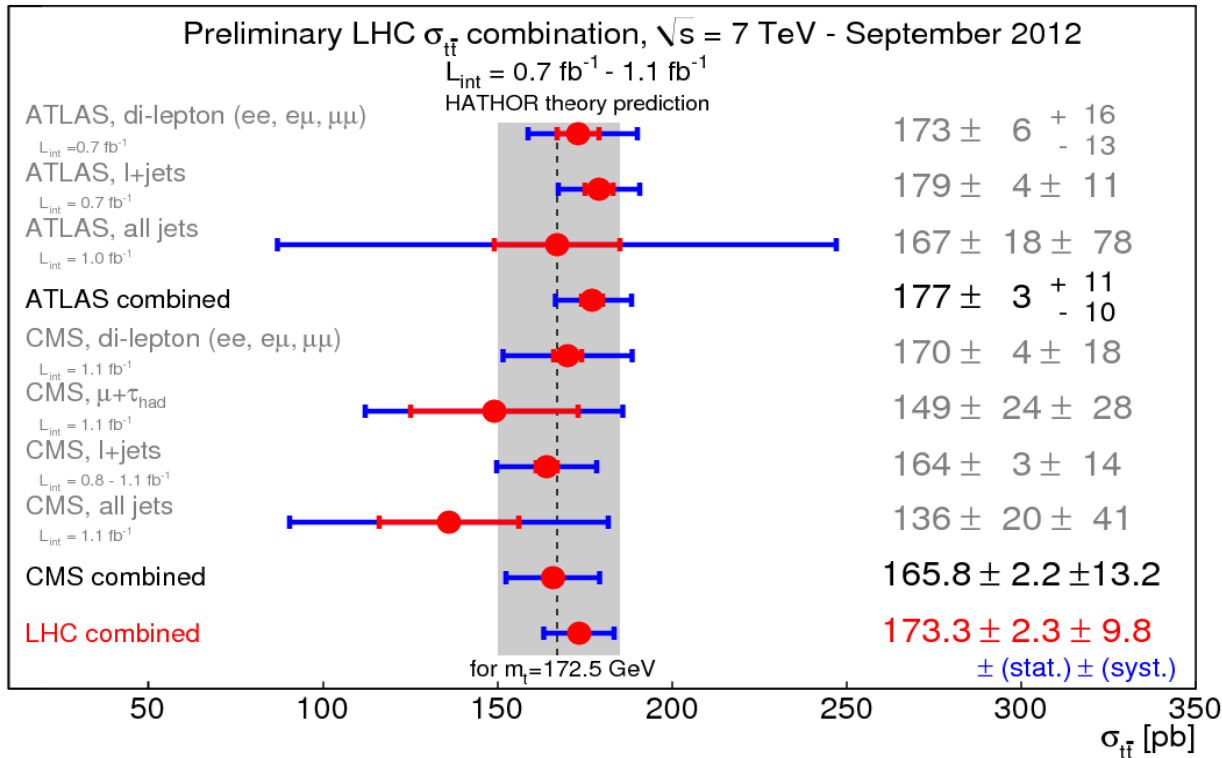
conveners: J. Pilot, J.Dolen, B.Tweedie, R.Poeschl, S.C.

- How well can top quarks be reconstructed at low energies and high energies, and *different pileup scenarios* ?
- What algorithms are available? Can they be improved? What is the impact of such improvements on physics questions discussed in the previous bullets?
- What is the energy resolution, identification and misidentification efficiency for each? What is required from the detector to be able to provide this?
- How can top quarks be used to improve b-tagging or jet energy resolution and other detector calibrations?



# Inclusive $t\bar{t}$ cross section. Unboosted regime.

- Top cross section reconstruction is dominated by systematic uncertainties



ATLAS-CONF-2012-134

Instrumental differences between CMS and ATLAS detectors  
But the physics output is similar!  
Common factors?



# Detector requirements can be different for

- **SM top-quark measurements**
  - masses, cross sections, forward-backward asymmetries,  $|V_{tb}|$ , etc.
  - discoveries can also be made by confronting measurements with SM predictions!
- **Searches that require top reconstruction**
  - searches that include measurements (i.e. limits based on rates, raw distributions, etc)
  - searches based on observation of distinctive “features” (“bumps” etc)

**Is any common systematic uncertainty for all such measurements?**

**What should we expect for future LHC runs?**

**What can be improved in future?**





# Detector uncertainties

- Uncertainties for lepton (muon/electron) identification
- Lepton (electron/muon) energy scale and resolution
- b jet identification efficiency and fake rates
- Jet energy and resolution uncertainties
- Uncertainties on missing transverse momentum

**Other uncertainties:** signal uncertainties, background uncertainties, method uncertainties, luminosity, top mass

**Top is ideal probe for detector performance since top reconstruction involves multiple aspects ranged from lepton identification to jets and missing ET**

**Best way to predict our feature is to look at the past**





# Cross sections & systematics. Unboosted regime.

ATLAS-CONF-2012-134

|                            | ATLAS | CMS   | Correlation | LHC combination |
|----------------------------|-------|-------|-------------|-----------------|
| Cross-section              | 177.0 | 165.8 |             | 173.3           |
| <b>Uncertainty</b>         |       |       |             |                 |
| Statistical                | 3.2   | 2.2   | 0           | 2.3             |
| Jet Energy Scale           | 2.7   | 3.5   | 0           | 2.1             |
| Detector model             | 5.3   | 8.8   | 0           | 4.6             |
| Signal model               |       |       |             |                 |
| Monte Carlo                | 4.2   | 1.1   | 1           | 3.1             |
| Parton shower              | 1.3   | 2.2   | 1           | 1.6             |
| Radiation                  | 0.8   | 4.1   | 1           | 1.9             |
| PDF                        | 1.9   | 4.1   | 1           | 2.6             |
| Background from data       | 1.5   | 3.4   | 0           | 1.6             |
| Background from MC         | 1.6   | 1.6   | 1           | 1.6             |
| Method                     | 2.4   | n/e   | 0           | 1.6             |
| W leptonic branching ratio | 1.0   | 1.0   | 1           | 1.0             |
| Luminosity                 |       |       |             |                 |
| Bunch current              | 5.3   | 5.1   | 1           | 5.3             |
| Luminosity measurement     | 4.3   | 5.9   | 0           | 3.4             |
| Total systematic           | 10.8  | 14.2  |             | 9.8             |
| Total                      | 11.3  | 14.4  |             | 10.1            |

Jet energy scale and detector model uncertainties are the dominant source of uncertainties

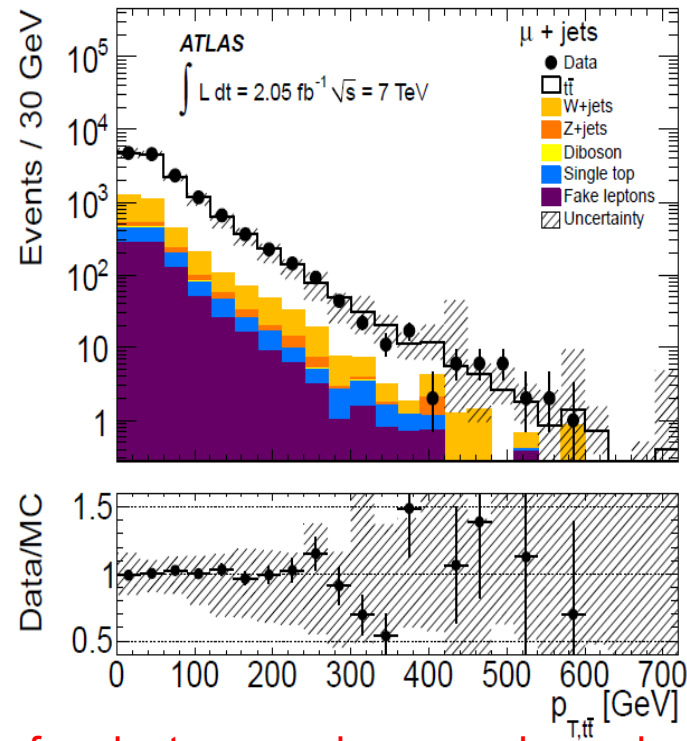
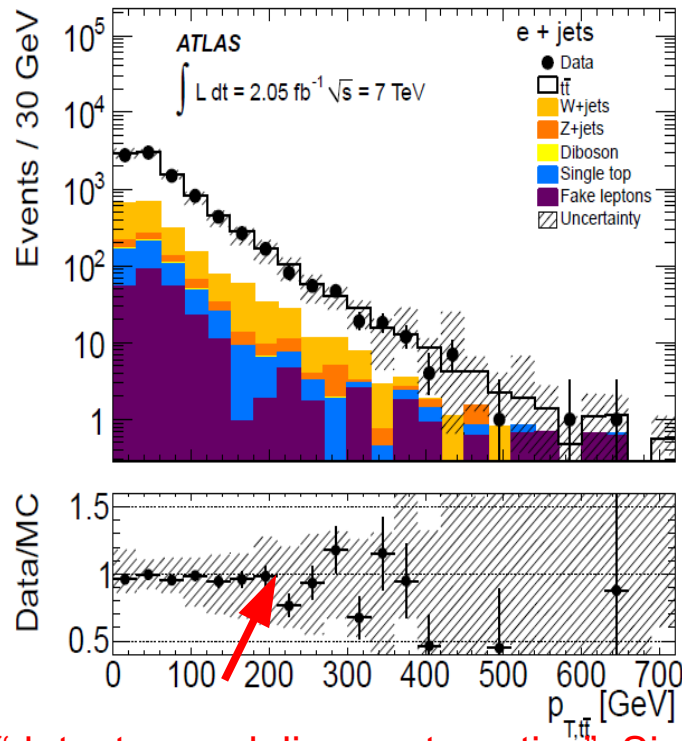
Luminosity uncertainties is less relevant (and can be reduced)





# Differential cross sections

Eur.Phys.J. C73 (2013) 2261



“detector modeling systematics”. Similar for electrons and muons channels

- Jet-energy resolution uncertainty: 9-17% ( $p_T \sim 30 \text{ GeV}$ ). 5-9% for  $p_T > 180 \text{ GeV}$
- The b-tagging efficiency uncertainty  $\sim 6$ -15%. Mistag rate 10-20%
- Jet energy scale ranges from  $\sim 3\%$  to 8%
- ET(mis) uncertainty ( $\sim 4\%$ )
- electron (muon) identification efficiency  $\sim 1$  (3%)





# Searches using $t\bar{t}$

| Systematic effect                        | Impact on yield [%] |                    | Impact on sensitivity [%] |
|--|---------------------|--------------------|---------------------------|
|  | background          | $Z'\text{1.3 TeV}$ |                           |
| Luminosity                               | 2.5                 | 3.7                | 0.4                       |
| PDF uncertainty                          | 3.1                 | 1.0                | 0.2                       |
| $t\bar{t}$ normalization                 | 4.9                 | —                  | 0.7                       |
| $t\bar{t}$ ISR, FSR                      | 6.3                 | —                  | 0.7                       |
| $t\bar{t}$ fragmentation & parton shower | 3.4                 | —                  | 0.9                       |
| $t\bar{t}$ generator dependence          | 2.8                 | —                  | 2.2                       |
| $W$ + jets normalization                 | 4.3                 | —                  | 1.4                       |
| $W$ + jets shape                         | <i>norm.</i>        | —                  | 0.1                       |
| Multijets normalization                  | 2.1                 | —                  | 0.2                       |
| Multijets shape                          | <i>norm.</i>        | —                  | 1.1                       |
| $Z$ + jets normalization                 | 2.0                 | —                  | 0.5                       |
| Jet energy and mass scale                | 6.7                 | 2.0                | 5.2                       |
| Jet energy and mass resolution           | 4.7                 | 4.0                | 1.2                       |
| Electron ID and reconstruction           | 1.1                 | 1.3                | 1.0                       |
| Muon ID and reconstruction               | 2.2                 | 2.1                | 4.8                       |

- Typically searches are less demanding when it comes to systematical and theoretical uncertainties (no unfolding!)

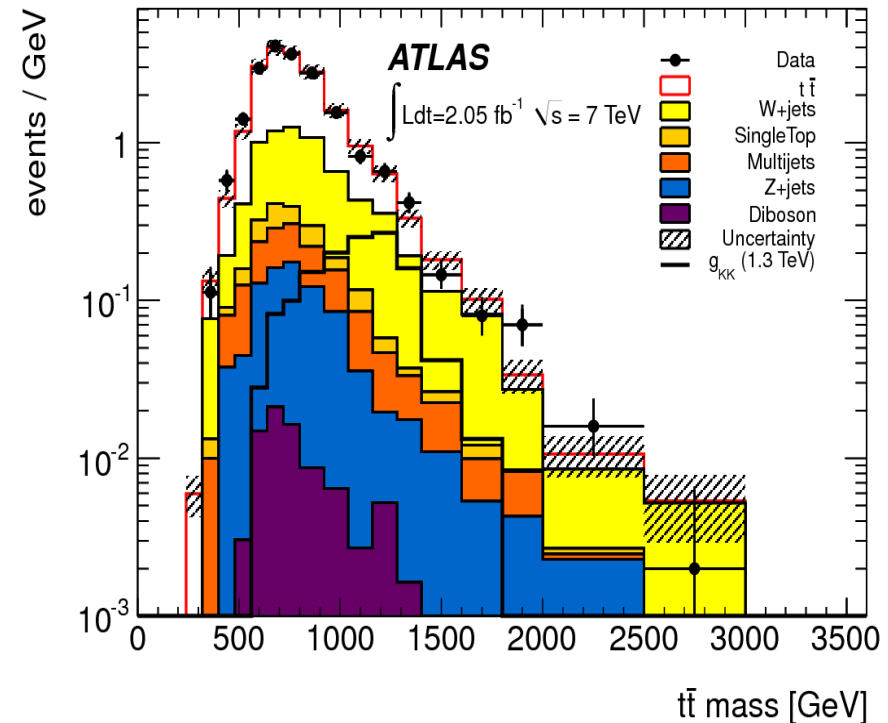
Phys. Rev. D 86, 091103 (2012)

<http://arxiv.org/abs/1207.2409>

**Same as before:**

Jet energy scale and resolution are largest contributors to systematic uncertainties

## lepton+jets events





# Top mass measurements

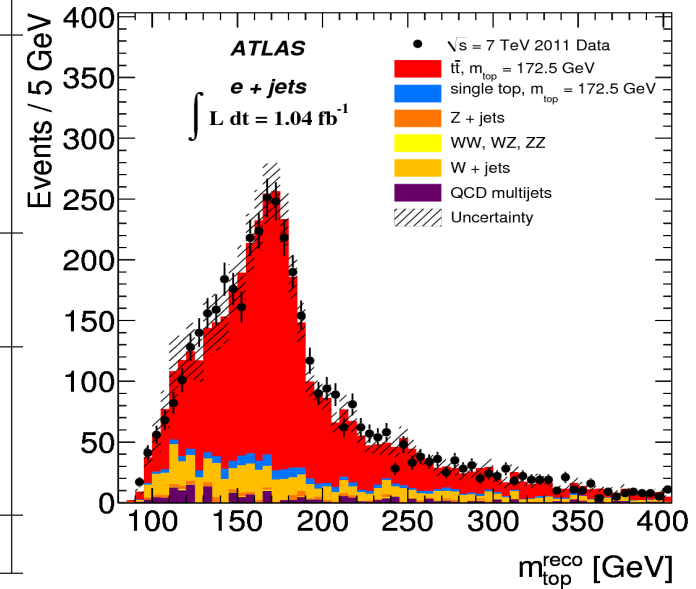
Eur.Phys.J. C72 (2012) 2046

$$m_{\text{top}} = 174.3 \pm 0.8_{\text{stat}} \pm 2.3_{\text{syst}} \text{ GeV} \quad (2d \text{ } e+\text{jets}),$$

$$m_{\text{top}} = 175.0 \pm 0.7_{\text{stat}} \pm 2.6_{\text{syst}} \text{ GeV} \quad (2d \text{ } \mu+\text{jets}).$$

|                                       | 1d-analysis |             | 2d-analysis |             | Combinations |        |
|---------------------------------------|-------------|-------------|-------------|-------------|--------------|--------|
|                                       | e+jets      | $\mu$ +jets | e+jets      | $\mu$ +jets | 1d           | 2d     |
| Measured value of $m_{\text{top}}$    | 172.93      | 175.54      | 174.30      | 175.01      | 174.35       | 174.53 |
| Data statistics                       | 1.46        | 1.13        | 0.83        | 0.74        | 0.91         | 0.61   |
| Jet energy scale factor               | na          | na          | 0.59        | 0.51        | na           | 0.43   |
| Method calibration                    | 0.07        | < 0.05      | 0.10        | < 0.05      | < 0.05       | 0.07   |
| Signal MC generator                   | 0.81        | 0.69        | 0.39        | 0.22        | 0.74         | 0.33   |
| Hadronisation                         | 0.33        | 0.52        | 0.20        | 0.06        | 0.43         | 0.15   |
| Pileup                                | < 0.05      | < 0.05      | < 0.05      | < 0.05      | < 0.05       | < 0.05 |
| Underlying event                      | 0.06        | 0.10        | 0.42        | 0.96        | 0.08         | 0.59   |
| Colour reconnection                   | 0.47        | 0.74        | 0.32        | 1.04        | 0.62         | 0.55   |
| ISR and FSR (signal only)             | 1.45        | 1.40        | 1.04        | 0.95        | 1.42         | 1.01   |
| Proton PDF                            | 0.22        | 0.09        | 0.10        | 0.10        | 0.15         | 0.10   |
| W+jets background normalisation       | 0.16        | 0.19        | 0.34        | 0.44        | 0.18         | 0.37   |
| W+jets background shape               | 0.11        | 0.18        | 0.07        | 0.22        | 0.15         | 0.12   |
| QCD multijet background normalisation | 0.07        | < 0.05      | 0.25        | 0.33        | < 0.05       | 0.20   |
| QCD multijet background shape         | 0.14        | 0.12        | 0.38        | 0.30        | 0.09         | 0.27   |
| Jet energy scale                      | 1.21        | 1.25        | 0.63        | 0.71        | 1.23         | 0.66   |
| b-jet energy scale                    | 1.09        | 1.21        | 1.61        | 1.53        | 1.16         | 1.58   |
| b-tagging efficiency and mistag rate  | 0.21        | 0.13        | 0.31        | 0.26        | 0.17         | 0.29   |
| Jet energy resolution                 | 0.34        | 0.38        | 0.07        | 0.07        | 0.36         | 0.07   |
| Jet reconstruction efficiency         | 0.08        | 0.11        | < 0.05      | < 0.05      | 0.10         | < 0.05 |
| Missing transverse momentum           | < 0.05      | < 0.05      | 0.12        | 0.16        | < 0.05       | 0.13   |
| Total systematic uncertainty          | 2.46        | 2.56        | 2.31        | 2.57        | 2.50         | 2.31   |
| Total uncertainty                     | 2.86        | 2.80        | 2.46        | 2.68        | 2.66         | 2.39   |

lepton+jets channel



Same as before:

Jet energy scale, resolution are the largest contributors to systematical uncertainty







# Experimental uncertainty for top measurement

“**Detector modeling**” is one of the most important contributions to top measurements

- “how well do we understand MC simulation used to evaluate efficiency and background rate”
- Hard question to answer using fast simulations
- A poor top signal in data cannot help to get good MC understanding!
- Understanding of jets (jet resolution, jet energy-scale uncertainty) and missing ET are the most crucial for top reconstruction





## How to improve top reconstruction?

- Improving jet reconstruction, missing ET and b-jet reconstruction
- Improving MC modeling of jets and missing ET (i.e. “understanding”)
- Improving various techniques to deal with pileup events

**Solving this will solve 80% of uncertainties for top reconstruction**

50 or 140 pileup events for future LHC runs will lead to more complicated jet reconstruction compared to 7-8 TeV runs with 5-20 pileup events (see next)

### CMS vs ATLAS

**Instrumental differences will be small for 50 and 140 pileup scenarios:**

- methods dealing with pileup events (and their understanding in MC simulations) will be more important than hardware instrumentation (see next)
- but can differences in the instrumentation between CMS and ATLAS lead to differences in the pileup removal methods?

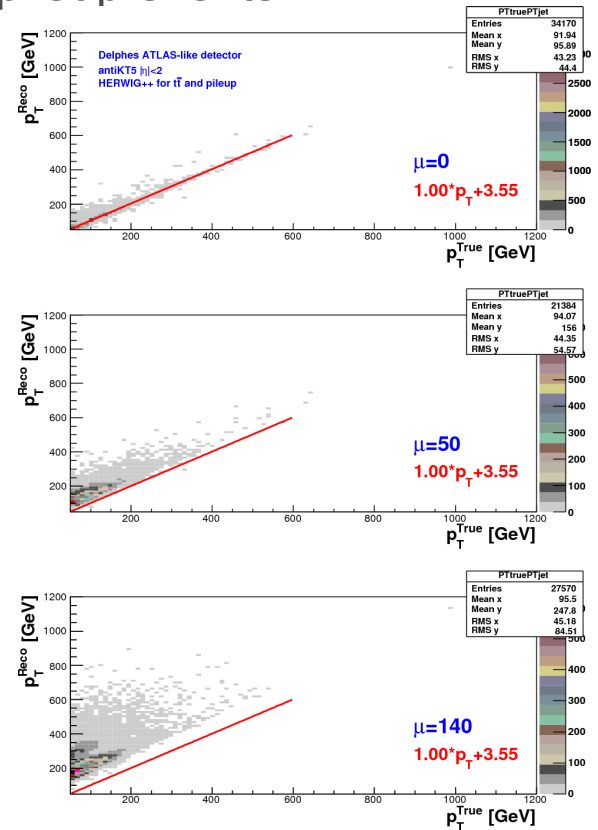
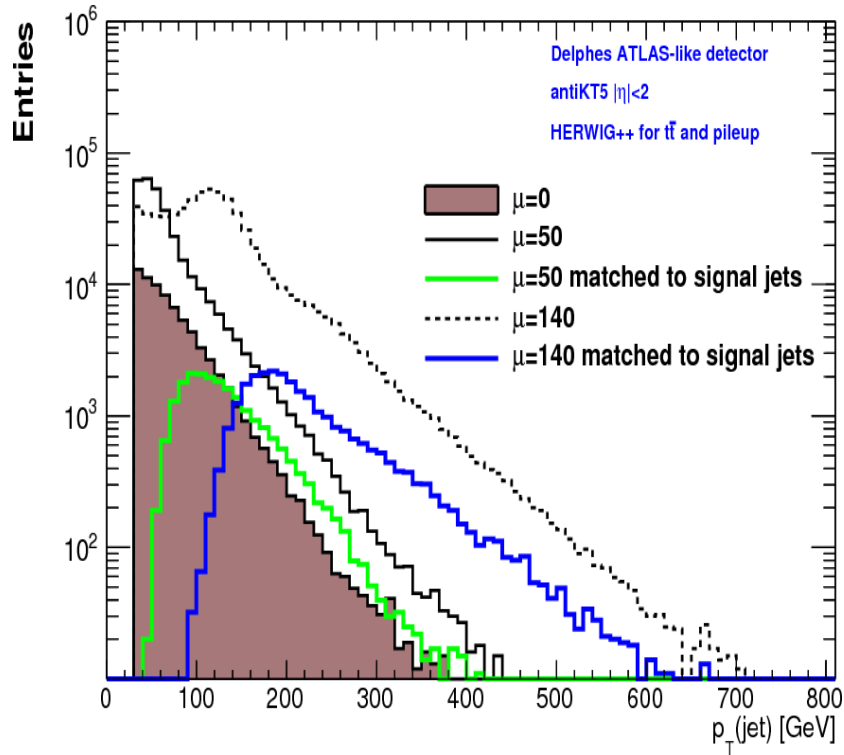




# Example: different pileup scenarios

(based on ATLAS-like Delphes simulation <https://atlaswww.hep.anl.gov/snowmass13>)

- What happens to jets after adding 50 or 140 pileup events?



Inclusive  $t\bar{t}$  measurements require 20-50 GeV jets

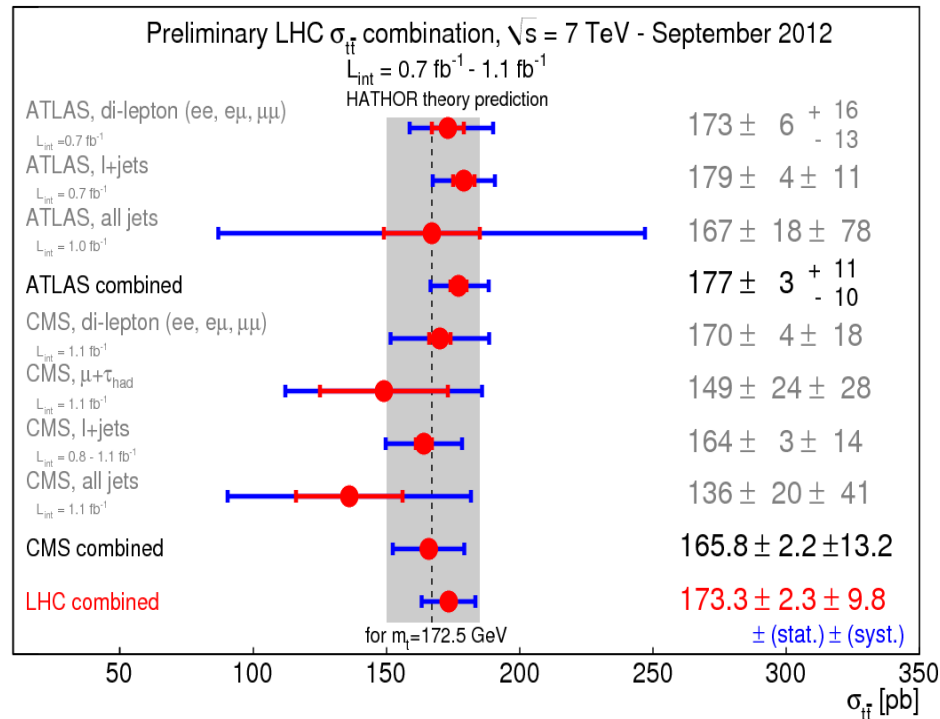
Such jets are substantially modified by 140 pileup events (large fake rate, energy shift)

**50 GeV jets become  $\sim 100$  GeV jets ( $\langle \mu \rangle \sim 50$ ) or 200 GeV jets ( $\langle \mu \rangle \sim 140$ )**





# Can we do better than what we see here?



Going into 140 or even 50 pileup scenario can only increase systematic uncertainty on the measurements (assuming same detector performance as for 2012)  
→ unless we become suddenly clever and start using a technique which effectively deals with pileup contribution to jets and missing ET (+ good MC modeling).

**Higher-luminosity LHC will become even more “discovery” machine and in a less degree “precision” measurement instrument. Are we disparate?**





# What is the future?

From the instrumental point of view, any low  $p_T$  top reconstruction **will unlikely** be improved for high-luminosity LHC runs with  $>50$ -140 pileup scenario

## What looks less promising (few examples):

- **Inclusive top jet cross sections**
  - will be done at 13-14 TeV (and must be done), but systematical uncertainties will likely increase ( $\sim 50$  GeV jets are very strongly affected by pileup)
- **Top-mass measurements**
  - the measurements will be dominated by systematical uncertainty (which will increase for high-lumi runs)
- **Rare processes that require low- $p_T$  jets**
  - associated Higgs production,  $t\bar{t}$ +jets, etc.

**Need for low pileup LHC runs ( $\sim 100$  pb $^{-1}$ ) at 13-14 TeV for high-precision SM measurements?**

**Perhaps a combination of LHC and CMS results may help to reduce systematic uncertainties for certain inclusive channels and bring them to the level close to theoretical uncertainty**





# What is the future?

## Promising:

- **$t\bar{t}$  cross sections and single top at high- $p_T$ :**
  - enough statistics, relatively small pileup effect
  - boosted jet techniques are useful (see the next talks) for  $p_T > 500\text{-}600\text{ GeV}$
- **Searches for high-mass states decaying to top quarks**
  - typically require high- $p_T$  top quarks & boosted technique
- **Studies of rare events involving top decays?**
  - Even systematically dominated measurements are important
- **What are the limitation of boosted top reconstruction due to finite spatial resolution of calorimeters? At what  $p_T(t)$  calorimeter segmentation is not sufficient to resolve top quarks? Track jets?**

Can be answered using available fast MCs <https://atlaswww.hep.anl.gov/snowmass13>

